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Abstract

LTE networks' main challenge is to efficiently use the available spectrum, and to provide satisfying quality of service for mobile users. However, using the same bandwidth among adjacent cells leads to occurrence of Inter-cell Interference (ICI) especially at the cell-edge. Basic interference mitigation approaches consider bandwidth partitioning techniques between adjacent cells, such as frequency reuse of factor m schemes, to minimize cell-edge interference. Although SINR values are improved, such techniques lead to significant reduction in the maximum achievable data rate. Several improvements have been proposed to enhance the performance of frequency reuse schemes, where restrictions are made on resource blocks usage, power allocation, or both. Nevertheless, bandwidth partitioning methods still affect the maximum achievable throughput. In this proposal, we intend to perform a comprehensive survey on Inter-Cell Interference Coordination (ICIC) techniques, and we study their performance while putting into consideration various design parameters. This study is implemented throughout intensive system level simulations under several parameters such as different network loads, radio conditions, and user distributions. Simulation results show the advantages and the limitations of each technique compared to frequency reuse-1 model. Thus, we are able to identify the most suitable ICIC technique for each network scenario.

Index Terms

Inter-Cell Interference Coordination, mobile networks, LTE, frequency reuse-3, FFR, SFR.

I. Introduction

Third Generation Partnership Project (3GPP) introduced Long Term Evolution (LTE) [1] standard to fulfill the increasing demand for data in mobile networks. LTE is a mobile network technology that substantially improves end-user throughputs [2], in order to meet the rapid growth in data demands. With the proliferation of mobile applications and the development of mobile equipment industry, mobile operators always seek to increase resource efficiency in order to make maximum use of the scarce available frequency spectrum. LTE chooses frequency reuse-1 model to improve system capacity and increase user satisfaction. Multiuser Orthogonal Frequency Division Multiple Access (OFDMA) [3] technique used for the radio interface on the downlink of LTE networks eliminates intra-cell interference, since data is transmitted over independent orthogonal subcarriers. Similarly, Single Carrier Frequency Division Multiple Access (SC-FDMA) technique, characterized by a lower peak-to-average power ratio [4], is used on the uplink to transmit data from users to the base station [5]. However, frequency reuse factor one leads to Inter-Cell Interference (ICI) strongly affecting SINR of active User Equipments (UEs), especially cell-edge UEs, which leads to a significant degradation in the total throughput. Moreover the existence of network elements with different maximum transmission power, $e.g.$, macrocells, picocells and femtocells, makes the ICI problem more complicated.

ICI arises as a prohibitive problem due to simultaneous transmissions over the same frequency resources in adjacent LTE cells. ICI decreases Signal-to-Interference plus Noise Ratio (SINR) especially for cell-edge UEs [6], that are relatively far from the serving evolved-NodeB (eNodeB). Thus, it has a negative impact on user throughput, it decreases spectrum efficiency, and it reduces the quality of provided services.

Hard frequency reuse schemes ($e.g.$, reuse factor m) become inefficient due to utilization of $\frac{1}{m}$ of available bandwidth that affects peak data rate. For instance, adjacent base stations of a Global System for Mobile communications (GSM) network are allocated different frequencies [7] in order to avoid interference between neighboring transmitters. A number of adjacent GSM cells are grouped into a cluster where the same frequency resources are used only once [8]. A cluster size of one is not used due to high co-channel interference problems that occur. Although ICI within each cluster is eliminated, spectral efficiency is largely reduced.

In Code Division Multiple Access (CDMA) scheme, the interference experienced by a user is due to cross-correlation between spreading codes, and it can be considered as noise [9]. Therefore, ICI problems do not exist in CDMA-based 3G networks. OFDMA scheme [10] is based on OFDM technology that subdivides the available bandwidth into a multitude of narrower mutually orthogonal subcarriers, which can carry independent information streams. A physical Resource Block (RB) is defined as 12 subcarriers in the frequency domain (180 kHz) and six OFDM symbols in the time domain, which is equivalent to one time slot (0.5 ms) [11]. RB and power allocation are performed periodically by the schedulers every Transmit Time Interval (TTI) that equals one millisecond.

Although frequency reuse-*m* models eliminate ICI, they are not adequate for LTE networks. In fact, one major objective of 3GPP LTE standard is to increase network capacity in order to accommodate additional UEs. According to reuse-*m* schemes, each base station is allowed to allocate a portion of the available spectrum. This restriction is not tolerated in LTE since it greatly reduces spectrum efficiency. Thus, other frequency and power allocation schemes are used to reduce ICI; they are commonly known as Inter-Cell Interference Coordination (ICIC) [12] techniques.

Fractional Frequency Reuse (FFR) [13] and Soft Frequency Reuse (SFR) [14] are distributed static ICIC techniques used to improve spectral efficiency of LTE. While FFR sets restrictions on RB allocation between the different UEs in each cell, SFR performs both radio resource management and power allocation for the used RBs. These techniques are independently used in each cell without any cooperation between adjacent base stations. Several works exploit the communications between adjacent eNodeBs to reduce ICI. In fact, signaling messages about RB and power allocation are exchanged between adjacent eNodeBs over X2 interface, that interconnects neighboring cells. For instance, a recently proposed technique divides ICIC problem into a multi-cell scheduling and a multi-user scheduling problem [15]. The former uses an On/Off approach to determine the restricted RBs for each evolved NodeB (eNodeB), while the latter attributes RBs to UEs according to their radio conditions. ICIC can also be seen as a cooperative problem where LTE base stations collaborate in order to find the power allocation mask that minimizes inter-cell interference [16]. It is an adaptive SFR scheme that reduces transmission power on RBs allocated for UEs that experience good radio quality (close to the base station). However, the time scale of the proposed algorithm is in order of tens of seconds, which is disadvantageous when the system state is quickly varying with time.

With the introduction of Coordinated Multi-Point (CoMP) transmissions [17] in LTE-Advanced (LTE-A) networks, ICIC techniques rely more on dynamic coordination between base stations. Scheduling decisions are improved when they are made jointly for a cluster of cells [18] thereby enhancing performance through interference avoidance. Small cells (including pico-cells, femto-cells and home eNodeBs) deployment [19] along with existing macro base stations brings out the challenge of ICIC in heterogeneous networks. Indeed, serious interference [20] problems occur due to co-channel deployments with the macro cells. Enhanced-ICIC (e-ICIC) techniques are used to allow for time-sharing of spectrum resources between macro base stations and small cells. Authors of [21, 22] surveyed the different ICIC techniques, and they classified them according to cell cooperation and frequency reuse patterns. However, some of the existing ICIC surveys only present qualitative comparisons [23] of ICIC techniques, while others perform simulations under uniform UE distributions and ordinary network scenarios.

Given the diversity of existing ICIC techniques, mobile network operators have the opportunity to implement the most convenient one for their intended objectives. In fact, the performance of some techniques largely depends on network parameters such as UE distribution between cell zones, existing ICI problems, and the number of UEs in each cell. Some techniques aim at improving cell-edge UEs throughput, without taking into account the overall spectral efficiency. Consequently, the knowledge of ICIC techniques performance is a critical factor when selecting the one that best fits operator's goals. In this article, we perform a comprehensive survey of the performance of ICIC techniques in LTE Networks. Various network loads, radio conditions, and user distributions are considered, in order to study the impact of design parameters on ICIC techniques performance. We investigate the performance of frequency reuse-m model and other ICIC techniques, and we classify them depending on the cooperation between network base stations. A MATLAB-based LTE downlink system level simulator [24, 25] is used to compare the performance of frequency reuse-1 model with reuse-3 model, FFR and SFR techniques. The objective of ICIC is to reduce interference problems in order to avoid their harmful impact on user throughput and system performance. An efficient ICIC technique improves both spectral efficiency and energy efficiency of the mobile network, which is a substantial goal for mobile network operators.

The rest of the article is organized as follows: in section II we explain frequency planning techniques used in GSM networks, we discuss interference problems in LTE, and we classify the existing ICIC techniques. Section III describes LTE system model, UE classification and SINR calculation. Details about simulation environment and performance metrics are given in section IV. Simulation results are reported in section V, and concluding remarks are presented in section VI.

II. ICIC Techniques

A. Frequency Planning Techniques for GSM Networks

The goal of frequency planning in GSM is to increase the capacity of the network while minimizing interference. After the first generation of analog mobile networks that use one single antenna transmitting at the maximum power, frequency reuse technique along with the cellular concept increase system capacity by allowing the usage of the same frequency resources in adjacent GSM clusters. The idea is to decrease cell size by reducing base station downlink transmission power in order to guarantee low co-channel interference.

Frequency allocation is planned taking into account the following issues: radio coverage, interference estimation and traffic distribution [26]. Traditionally, adjacent GSM cells are grouped into clusters where only a portion of the available spectrum is used in each cell. Therefore, we reduce ICI since frequency resources are not simultaneously used by adjacent base stations. If m is the number of cells within a cluster (also called: cluster size), then $\frac{1}{m}$ of the available subcarriers are used in each cell according to frequency reuse-*m* model. Figure 1 illustrates a GSM network where frequency reuse-3 model is used to manage frequency resources distribution between the different cells.

Although frequency reuse-*m* model mitigates ICI, the main disadvantage of such technique is that it reduces network capacity. With less resources available in each cell, the operator is not able to accommodate all the existing UEs. Thus the quality of the provided services is degraded, and user satisfaction is negatively impacted, especially when the number of UEs per cell increases. A possible alternative is to reduce cluster size when the number of UEs or their generated traffic increases. Thus, frequency planning in GSM can be seen as a compromise between network capacity and interference mitigation.

A dynamic channel allocation strategy is introduced in [27] where authors use the information exchanged between base stations in order to avoid conflicting carrier acquisitions. Frequency allocation between the different cells is tuned in real time, based on the average traffic and UE

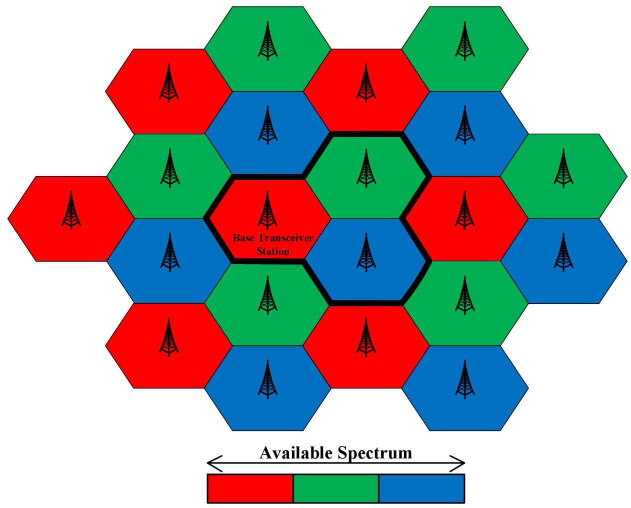

Fig. 1: Frequency reuse-3 model in GSM

speed in the cells. Multiple reuse patterns is another method to achieve high capacity using tight frequency reuse in combination with frequency hopping [28]. The idea is to apply different separate reuse patterns with different degrees of tightness and use frequency hopping to combine them into an average reuse.

B. ICIC in LTE Networks

The huge increase in the number of mobile subscribers, technology advances in UE industry and the proliferation of mobile applications have led to the usage of frequency reuse-1 model in LTE. The objective is to make use of all the available spectrum in order to deal with the tremendous need for data in mobile networks. The main drawback of universal frequency reuse systems is ICI caused by simultaneous transmissions scheduled on the same frequency resources by nearby base stations [29]. ICI reduces spectrum efficiency, decreases the average throughput per UE, and has a negative impact on the quality of the provided services. Thus, operators have great interest in implementing ICIC techniques to increase spectrum profitability and to improve UE experience.

1) Fractional Frequency Reuse: FFR [30] is a traditional distributed static ICIC technique. It does not require any cooperation between network eNodeBs. Each cell is statically divided into cell-center and cell-edge zones. The former contains UEs close to the base station, while the latter contains UEs close to the border of the cell. Since they are closer to the neighboring cells and relatively far from their serving eNodeBs, cell-edge UEs will experience more ICI. Therefore, the main objective of FFR is to protect RBs attributed for these UEs from interference problems.

FFR modifies RBs distribution between the different zones of the cell in order to create a *protected* set of RBs for cell-edge UEs. Figure 2 illustrates a cluster of three LTE cells where spectrum allocation between cell-center and cell-edge zones is done according to FFR technique. Cell-center UEs are also called Full Reuse (FR) UEs since their allocated spectrum is used according to frequency reuse-1 model in the neighboring cells. RBs allocated for the protected UEs are called Partial Reuse (PR) RBs since their usage in the adjacent cells is based on frequency reuse-3 model.

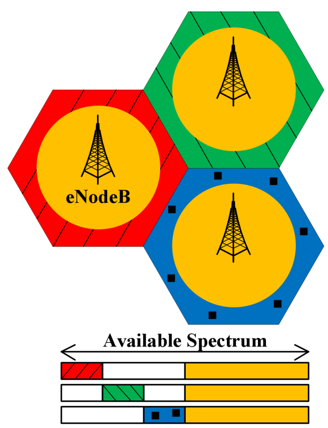

Fig. 2: Fractional frequency reuse technique

Although FFR reduces ICI for cell-edge UEs, the main drawback of this static ICIC technique is that it does not dynamically adapt RB distribution between cell zones according to user demands in each zone. In addition, UE geographical classification requires the knowledge of the exact position of all the active UEs in the network. Thus, an additional positioning information is required to determine cell-center and cell-edge UEs.

2) Soft Frequency Reuse: In the downlink of a multiuser OFDMA system, such as LTE, Signal to Interference and Noise Ratio (SINR) for a UE k on the RB n in the cell i is given by:

$$\mathrm{SINR}_{k,n}^{i} = \frac{P_n^i \cdot G_{k,n}^i}{\sum_{j \neq i} P_n^j \cdot G_{k,n}^j + P_{TN}}, \tag{1}$$

where P_n^i is the downlink transmission power allocated by the base station i for the RB n, $G_{k,n}^i$ is channel gain for UE k served by eNodeB i on RB n, and P_{TN} is the thermal noise power on the considered RB. The achievable rate on RB n for UE k in the cell i is therefore given by:

$$R_{k,n}^{i} = f(\mathrm{SINR}_{k,n}^{i}), \tag{2}$$

where $f(.)$ is the adaptive modulation and coding function that maps SINR to rate. SFR is another static ICIC technique where both RB distribution and downlink power allocation are performed to reduce ICI [31]. We define $\overline{\mathrm{SINR}}_k^i$ as the mean wideband SINR for UE k served by eNodeB i. It is the mean value of $\mathrm{SINR}_{k,n}^i$ for the considered UE over all the available RBs. This entity gives us information about the average channel quality, radio conditions, and ICI for UE k, since SINR is a function of the useful received power and the interfering received power. Instead of using geographical positions, mean wideband SINR values are used to classify UEs. If mean SINR of a UE is lower than a predefined SINR threshold, it is considered as a Bad Radio (BR) conditions UE; otherwise, it is classified as Good Radio (GR) conditions UE. BR UEs are commonly known as cell-edge UEs, while the remaining UEs are called cell-center UEs. Figure 3 shows the basic principles of SFR technique.

In each cell, a portion of the available spectrum is reserved for the cell-edge UEs, and it is permanently allocated the maximum downlink transmission power. The remaining RBs are allocated for cell-center UEs, but with a lower transmission power [32]. In addition, there is no common spectrum allocated for cell-edge UEs of the adjacent cells.

C. ICIC Techniques Classification

Rather than promoting standardized techniques, 3GPP provides support for proactive and reactive schemes, and it allows constructors and operators to configure a wide range of non-standardized ICIC algorithms [21]. ICIC techniques such as soft frequency reuse and fractional

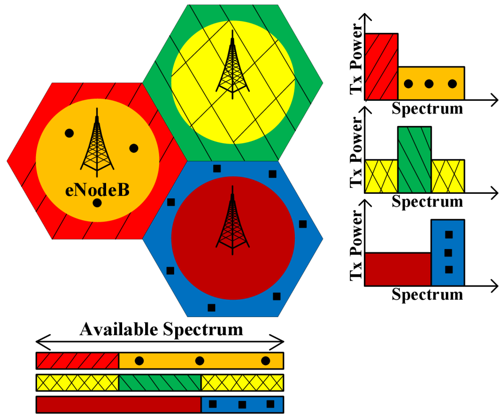

Fig. 3: Soft frequency reuse technique

frequency reuse have been widely suggested to minimize interference between adjacent cells and increase bandwidth efficiency. Several recent works have investigated the performance of existing ICIC techniques through intensive survey work as in [33, 34], where detailed survey on ICIC techniques and proposed modifications have been studied.

Several techniques are proposed to mitigate inter-cell interference that negatively impacts the performance of LTE networks. Resource allocation and interference coordination problems are jointly considered in [35]. The proposed technique is based on FFR scheme, and it searches for the optimal dimensions of cell-center and cell-edge zones as well as the optimal frequency reuse factor. Authors of [36] introduce a heuristic downlink power allocation strategy to reduce ICI. Power is allocated for each RB according to the received Channel Quality Indication (CQI) feedbacks. Another technique proposed in [37] performs power allocation according to SINR level for each RB. Then a circular shift is applied to the downlink power vector of each cell (while the others remain unchanged) in order to maximize the utility function. Other ICIC techniques are based on game-theoretic approaches [38, 39]. Bandwidth allocation, admission control, and ICI mitigation are achieved through distributed and interactive decision making, in order to reach the equilibrium point.

An interference avoidance scheme is presented in [40] where the objective is to mitigate interference for cell-edge UEs without reducing network throughput. The algorithm operates at the base station level and at a central controller to which a group of base stations are connected. Techniques based on interference graph approach are studied in [41, 42]. X2 interface that connects each eNodeB to its neighboring cells is exploited to exchange information related to interference levels, UE density, RB usage, and power allocation in each cell. They make use of base station cooperation in order to reduce ICI, and to improve system throughput. A flexible bandwidth allocation scheme for partial frequency reuse is described in [43] where RBs are dynamically allocated for cell zones.

We classify ICIC techniques into static models (or frequency reuse-based models), autonomous distributed [44] techniques, coordinated distributed techniques and centralized models. Static ICIC is based on frequency reuse schemes such as reuse-3 model. Autonomous distributed techniques meet the particularity of LTE architecture, where there is no central entity that controls network eNodeBs. However, coordinated distributed methods make use of the indicators exchanged between the neighboring eNodeBs via X2 interface to allocate RBs in adjacent cells in a way that reduces ICI. With the introduction of LTE-A [45], operators can benefit of the centralized control entities that manage several eNodeBs simultaneously. Therefore, the usage of centralized ICIC techniques [46] leads to a better RB distribution between all the network cells. Figure 4 summarizes the classification of ICIC techniques.

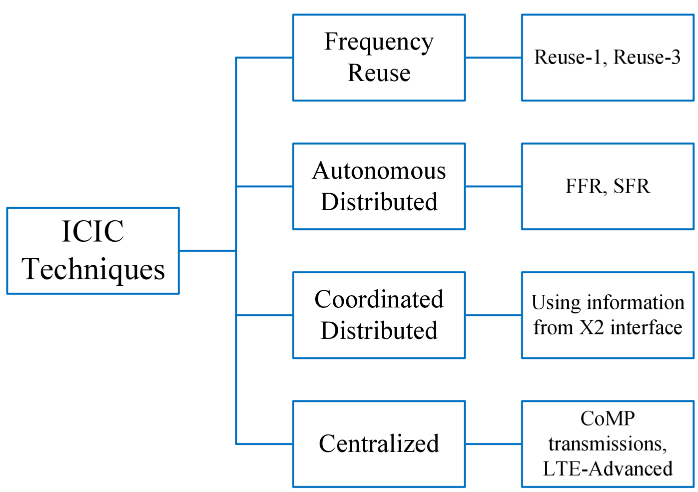

Fig. 4: Classification of ICIC techniques

D. CoMP Transmissions and Enhanced-ICIC

3GPP introduced coordinated multipoint transmission and reception techniques to facilitate cooperative communications for LTE-A system [47]. In CoMP, several cells coordinate with each other in such a way that the transmitted signals do not incur serious interference or even can be exploited as a meaningful signal. CoMP techniques [48] target more dynamic interference coordination, and they may require very low latency in comparison with ICIC techniques using information carried over X2 interface (latency is not guaranteed to be low). For instance, some techniques allow the transmission of the same data signals by different base stations instead of transmitting interfering signals. System performance is therefore improved using joint transmission, but additional signaling messages for base station coordination are required.

ICI problems in heterogeneous networks [49] arise as a new challenge with the extensive deployment of small cells (including femto and pico cells). For instance, an optimal FFR scheme for channel allocation is proposed in [50], where macrocell coverage is partitioned into cell-center and cell-edge zones with six sectors in each zone. The available spectrum is allocated in a manner that reduces co-tier interference in comparison with FFR. In addition, intracell cross-tier interference is reduced. Interference mitigation techniques proposed for multi-cell multi-antenna networks exploit cell cooperation to achieve coordinated scheduling [51], where RBs are allocated in the different cells without causing serious interference problems. ICIC should not only determine RBs distribution between macro and small cells, but it should also set association rules that decide which UE must be connected to small cells. These techniques are called e-ICIC, and they allow for time-sharing of spectrum resources (for downlink transmissions) between macro and pico cells so as to mitigate interference to small cells in the downlink [52]. In e-ICIC, a macro eNodeB can inject silence periods in its transmission schedule from time to time, so that interfering small cells can use those silence periods for downlink transmissions.

III. System Model

A. Deployment Model

Our system model consists of seven adjacent Macro Base Stations (MBS) serving active UEs within their coverage area. MBS coverage is modeled as a sectorized hexagonal layout [53], as shown in Fig. 5, and CI denotes the cell identifier. Each site consists of three adjacent hexagonal sectors, where each sector is served by an eNodeB having its own scheduler, bandwidth, and power allocation policy.

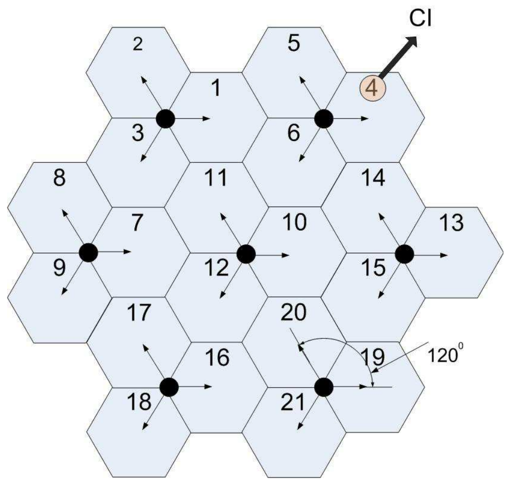

Fig. 5: Cell layout

B. Propagation Model

The system developed is based on the home eNodeB to UE path loss (PL) models. The models which are considered accurate are mentioned in [54] and [55]. PL calculation for signals traveling from the serving eNodeB to the UE is given by:

$$PL = 15.3 + 37.6 \log_{10}(D), \tag{3}$$

where PL is the path loss from MBS to UE, and D (in meters) is the distance between the active UE and its serving eNodeB.

C. Antenna Gain Model

Antenna pattern can be expressed as following:

$$A(\theta) = -\min(12(\frac{\theta}{\theta_{3dB}})^2, 20) \text{ [in dB]}, \tag{4}$$

$$-180^\circ < \theta < 180^\circ, \tag{5}$$

TABLE I: SINR-Data Rate Mapping Table

Minimum SINR [dB]	**Modulation and Coding Scheme**	**Data Rate [kbit/s]**
1.7	QPSK(1/2)	168
3.7	QPSK(2/3)	224
4.5	QPSK(3/4)	252
7.2	16QAM(1/2)	336
9.5	16QAM(2/3)	448
10.7	16QAM(3/4)	504
14.8	64QAM(2/3)	672
16.1	64QAM(3/4)	756

where $A(\theta)$ is antenna gain, and θ_{3dB} is the beamwidth, which is equal to $70°$.

D. SINR-Data Rate Mapping

As stated in (2), the value of achievable data rate that can be attained by a UE is a function of the SINR value. Table I shows the mapping of SINR values to data rates [56]. In our simulations, the single antenna transmission scheme is used. It is the transmission mode 1 as specified by 3GPP [45].

E. UE Distribution

Given the impact of UE distribution between cell zones on ICIC techniques performance, we consider the percentage of GR or BR UEs as an essential parameter to evaluate the compared techniques. In fact, UEs geographical positions, as well as UE distribution between cell zones have a great impact on ICI, and on the achievable throughput in each zone. Various UE distributions are considered in our simulations. We simulate scenarios where UEs are uniformly distributed between GR and BR zones, and other scenarios characterized by non-homogeneous UE distributions. For instance, the majority of active UEs are either in GR zone or in BR zone.

IV. Simulation Scenarios

A. Simulation Environment

We use a MATLAB-based LTE downlink system level simulator [24, 25], developed by Vienna University of Technology as the simulation platform. Frequency reuse-1 model and FFR technique are included in the original version of the simulator. However, homogeneous power allocation is only considered. We adjusted the power allocation scheme in order to allow allocating different power levels to the available RBs. We have also integrated SFR technique and reuse-3 model along with the existing FFR and reuse-1 schemes. Simulation parameters for the simulated LTE system [1, 57] and the ICIC techniques are summarized in Table II.

Cell geometry for our simulated LTE system is hexagonal, and each LTE site consists of three adjacent hexagonal sectors, where each sector is served by an eNodeB. Inter-eNodeB distance equals 500 m, which corresponds to an LTE network deployed in an urban area. In each cell, 25 RBs are available, since the operating bandwidth equals 5 MHz. However, traffic model is full buffer $i.e.$, all the available RBs are permanently allocated for the active UEs in the network. UE scheduling is performed every one millisecond. Path loss model is the one defined by 3GPP in [54, 55], and feedback reception at eNodeBs is delayed by three milliseconds. The distribution of the shadow fading is log-normal. Its standard deviation equals 6 dB for urban deployments, as specified by 3GPP technical specifications [57]. We note that when the shadow fading increases, the useful signal power and the interfering signals power are both reduced. For the frequency reuse-3 model, interference is null since each cell uses a disjoint portion of the available spectrum. Thus, SINR is reduced since it is proportional to the useful signal power, and UE throughput is reduced. For the frequency reuse-1 model, FFR, and SFR schemes, the useful signal power and the interfering signals power are both reduced. Compared to the useful signal power, the interfering signals power is more reduced since it is the sum of several signals transmitted by the neighboring cells. Thus, SINR degradation is lower than that of the frequency reuse-3 model. However, the relative comparison of these techniques when compared to each other remains the same. When homogeneous power allocation is used, the maximum downlink transmission power is allocated for each RB. However, SFR reduces the transmission power allocated for RBs used by GR UEs. SINR$_{threshold}$ is a predefined parameter, used to classify active UEs into GR and BR UEs. It can be adjusted by mobile network operators according to network load and UE satisfaction.

Unlike traditional works where the proposed interference mitigation technique is compared to reuse-1 and reuse-*m* models under ordinary network conditions ($e.g.$, homogeneous UE density and uniform UE distribution), we investigate ICIC techniques under various simulation scenarios. We study the impact of network load (number of UEs per eNodeB) and UE distribution (percentage of GR UEs in the network) on system performance for each of the compared techniques. For instance, we consider homogeneous UE density among all the cells, and we start increasing the number of active UEs per cell. Therefore, we show the impact of network load on UE satisfaction for reuse-1 model and other ICIC schemes. This study allows us to choose the most adequate technique for each network load scenario $e.g.$, system performance is improved when using a specific ICIC technique when the network is highly loaded, whereas reuse-1 offers a better performance for other scenarios. In addition, we consider not only uniform UE distributions, but also scenarios where UEs are not uniformly distributed between cell-zones. Thus, we study the impact of UE distribution on the chosen ICIC technique, and we show the evolution of system performance when the percentage of GR UEs changes.

B. Performance Metrics

In order to compare the performance of the studied techniques, we define the following performance comparison criteria:

1) Spectral Efficiency and Energy Efficiency: The objective of mobile network operators is to increase the profitability of the available spectrum while reducing power consumption. Let *K* denote the set of active UEs in the network, I the set of eNodeBs, and N the set of available RBs in each cell. $\overline{R}_k$ is the mean throughput achieved by UE k, and P_n^i the downlink transmission power allocated by cell i to RB n. Spectral efficiency and energy efficiency [60] are therefore defined as follows:

$$\text{Spectral efficiency} = \frac{\sum\limits_{k=1}^{K} \overline{R}_k \text{ [bit/s]}}{\text{Total spectrum [Hz]}}, \tag{6}$$

TABLE II: Simulation Parameters

Parameter	Value	Description
Cell geometry	Hexagonal	A cell is served by an eNodeB
Number of sites	7	—
Inter-eNodeB distance	500 m	Urban area
Operating bandwidth	5 MHz	—
Number of RBs	25	In the 5 MHz bandwidth
Transmission frequency	2 GHz	—
Subcarrier frequency	15 kHz	1 RB = 12 sub-carriers
RB bandwidth	180 kHz	12×15 kHz
TTI	1 ms	Transmit Time Interval
Thermal noise density	-174 dBm/Hz	—
Feedback delay	3 ms	3 TTIs
Scheduler	Round Robin	—
Traffic model	Full buffer	—
eNodeB maximum power (P_t)	20 W	43 dBm
Maximum power per RB	0.8 W	$\frac{P_t}{\text{nb. of RBs}}$
$\text{SINR}_{\text{threshold}}$	5 dB	UE classification [58, 59]
Number of UEs per sector	2, 5, 7, 10, 15, 20	Impact of network load
Antenna gain	14 dBi	—
Penetration Loss ($PenL$)	10 dB	—
Pathloss model	$15.3 + 37.6 \log_{10}(D)$	As in [54, 55]; D in m
Shadow fading (ζ)	Log-normal distribution	Standard deviation = 6 dB [57]
Simulation time	1000 TTIs	—

$$\text{Energy efficiency} = \frac{\sum_{k=1}^{K} \overline{R}_k \text{ [bit/s]}}{\sum_{i=1}^{I} \sum_{n=1}^{N} P_n^i \text{ [W]}}. \tag{7}$$

2) UE Throughput: In order to investigate the impact of each technique on UE performance in each zone and on the overall system performance, we use the following metrics:

- *Mean throughput per UE* [Mbit/s]
- *Mean throughput per GR UE* [Mbit/s]
- *Mean throughput per BR UE* [Mbit/s]

For each simulation run, mean throughput is the average throughput achieved by UEs throughout the simulation time. These three metrics give an overview about how the throughput of each zone is modified when applying an ICIC technique. Thus, they allow to carry out a more detailed performance comparison using significant throughput information.

3) Fairness Index: Fairness in resource sharing is an important performance comparison parameter. Jain's fairness index [61] is given by:

$$\mathrm{J}(\overline{R}_1, \overline{R}_2, ..., \overline{R}_K) = \frac{(\sum\limits_{k=1}^{K} \overline{R}_k)^2}{K.\sum\limits_{k=1}^{K} \overline{R}_k^2}, \tag{8}$$

where J rates the fairness of a set of throughput values; K is the number of UEs, and $\overline{R}_k$ is the mean throughput of UE k. Jain's fairness index ranges from $\frac{1}{K}$ (worst case) to 1 (best case). It reaches its maximum value when all UEs receive the same throughput. An efficient ICIC technique reduces the gap between GR and BR UEs throughputs, and increases Jain's fairness index.

4) UE Satisfaction: We define a satisfaction throughput threshold as the reference value for performance comparison. It is the minimum throughput value required to guarantee an acceptable quality of service. A UE is qualified as satisfied if its average throughput is higher than satisfaction threshold; otherwise, this UE will be considered as unsatisfied.

The percentage of unsatisfied UEs among all the active UEs in the network is another parameter for performance comparison. An ICIC technique is better than other state-of-the-art techniques when it shows the lowest percentage of unsatisfied UEs. We also investigate the evolution of this percentage when network load increases.

5) Throughput Cumulative Distribution Function (CDF): This metric shows UE throughput distribution for the studied ICIC techniques. For each throughput value, CDF represents the probability to find a UE characterized by a lower throughput. Therefore, when comparing interference mitigation techniques, the best one is the one showing the lowest CDF for all throughput values.

V. Simulation Results and Analysis

A. Spectral Efficiency versus Energy Efficiency

We simulate an LTE network that consists of seven adjacent cells, with 10 UEs randomly placed in each cell. Operating bandwidth is 5 MHz; therefore, 25 RBs are available in each cell. Simulation time is 100 TTIs, and traffic model is full buffer $i.e.$, all the available RBs are assigned to the active UEs. Consequently, inter-cell interference occur over all the available RBs, since they are permanently used for downlink transmissions, even when the number of UEs per cell is low. Simulations are repeated 100 times, where UE positions and radio conditions are randomly generated each time. The obtained results are illustrated in Fig. 6.

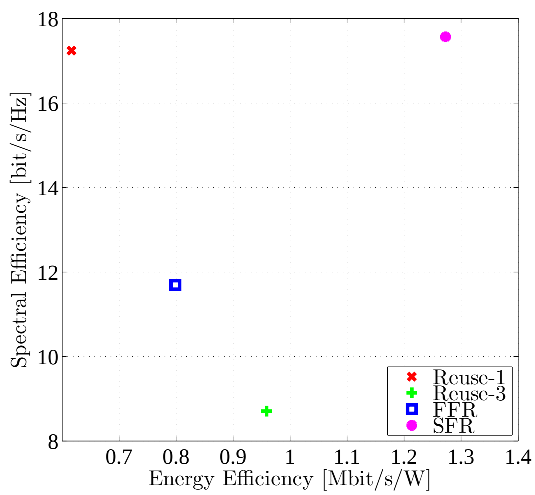

Fig. 6: Spectral efficiency versus energy efficiency

Reuse-1 model shows the lowest energy efficiency, since the maximum downlink transmission power is permanently allocated to all the available RBs. However, its spectral efficiency is comparable to that of SFR, and higher than that of FFR and reuse-3 models: reuse-1 makes maximum use of the existing RBs, without any constraint on frequency usage. FFR technique reduces power consumption, and improves energy efficiency in comparison with reuse-1 model. Nevertheless, there is an unused frequency sub-band in each cell; thus, spectral efficiency is reduced.

Reuse-3 model shows the lowest spectral efficiency: only one third of the available spectrum is used in each cell (for a cluster of three adjacent cells), while it increases energy efficiency in comparison with reuse-1 and FFR. SFR improves both spectral and energy efficiencies, in comparison with dense frequency reuse model and other ICIC techniques. It uses a frequency reuse factor of one with restrictions on power allocation; thus, it is able to improve energy efficiency without sacrificing spectral efficiency.

B. Mean Throughput per Zone

For the same simulated network, we study the impact of each of the compared techniques on UE throughput in GR and BR zones, as well as mean throughput per UE. For FFR, 36% of the available spectrum is used by GR UEs, the remaining bandwidth is allocated for BR UEs, according to reuse-3 model in the adjacent cells. When SFR technique is used, one third of the available spectrum is used at the maximum transmission power by BR UEs, while the remaining two thirds are allocated for GR UEs at a lower transmission power. For reuse-3 technique, all the active UEs in each cell are considered as BR UEs, and one third of the available spectrum is allocated to them. Mean throughput for GR and BR zones as well as mean throughput per UE are shown in Fig. 7.

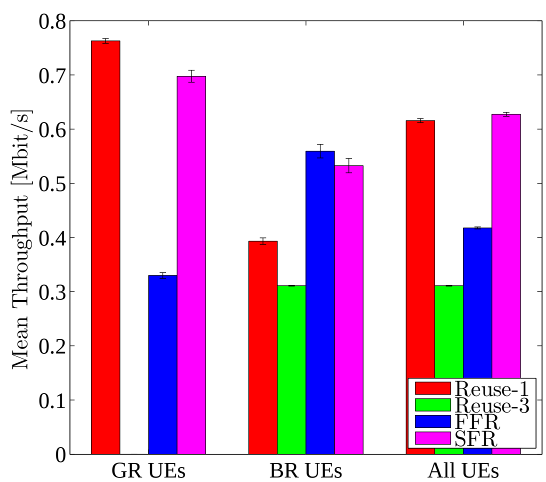

Fig. 7: Mean Throughput per GR, BR, and all UEs

We notice that FFR technique succeeds in improving BR UEs throughput, in comparison with reuse-1, reuse-3 and SFR techniques. It prohibits the usage of the same sub-band not only in adjacent BR zones, but also in any other GR zone of the considered cluster. Although ICI is mitigated for BR UEs, frequency sub-bands available in GR zones become smaller, and FFR reduces the average throughput per UE when compared to reuse-1 model. Reuse-3 aggravates the disadvantage of FFR, since only one third of the available spectrum is used by active UEs in each cell. Thus, mean throughput per UE reaches its lowest value with reuse-3 model. SFR technique improves BR UEs throughput without reducing mean throughput per UE for the entire network. The power allocation strategy applied by SFR reduces ICI for BR UEs. Thus, it maximizes the usage of the available spectrum in all network cells, and reduces ICI simultaneously.

C. Throughput Cumulative Distribution Function

We report throughput CDF for the compared techniques, under the same simulation scenario. It allows us to study throughput distribution among active UEs in the network. CDF for reuse-1, reuse-3, FFR, and SFR techniques is illustrated in Fig. 8.

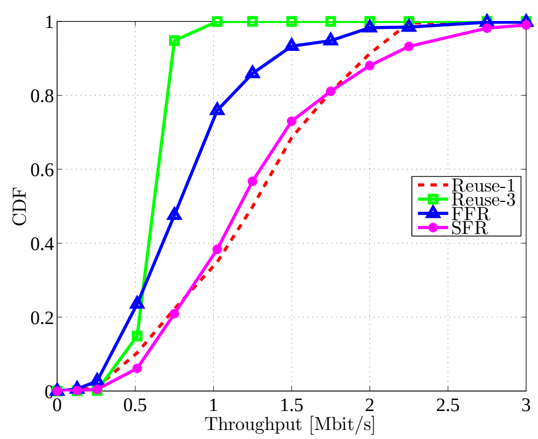

Fig. 8: Throughput cumulative distribution function

For a given throughput value, CDF represents the probability to find a UE characterized by a lower throughput. The lower the CDF is, the better the quality of service is. We notice that throughput CDF of reuse-3 model is the first to reach the maximum. In other words, the probability to find a UE served with a throughput less than 1 Mbit/s equals one. FFR improves throughput CDF function in comparison with reuse-3. However, it reaches the maximum before reuse-1 CDF. When using SFR, the number of UEs suffering of bad quality of service is reduced. For relatively low throughput values (less than 1 Mbit/s) throughput CDF for SFR is the lowest curve; thus, it shows the lowest percentage of UEs served with low throughputs. Moreover, SFR curve is the last one to reach its maximum (at 3 Mbit/s approximately). Consequently, when mobile network operators seek to improve throughput CDF for the entire system, SFR is the most adequate technique among the compared ICIC schemes. It succeeds in reducing the percentage of UEs with relatively low throughputs, while also improving the maximum achievable throughput in the network. Through restrictions made on downlink transmission power allocation, SFR reduces ICI for BR UEs, and provides enough bandwidth for GR UEs to achieve higher data rates.

D. UE Satisfaction versus Network Load

In this paragraph, we compare the percentage of unsatisfied UEs for each technique. The simulated network consists of seven adjacent hexagonal LTE cells. We simulate several scenarios, where the number of UEs per cell is increased. For each scenario, simulations are repeated 100 times, and the obtained results are illustrated in Fig. 9. Satisfaction throughput threshold is set to 512 kbit/s. We assume that the average throughput per UE is required to be higher than 512 kbit/s in order to fulfill its downlink data traffic demands. If the average throughput of a UE is higher than this threshold, it is considered as satisfied; otherwise, this UE is considered as an unsatisfied UE.

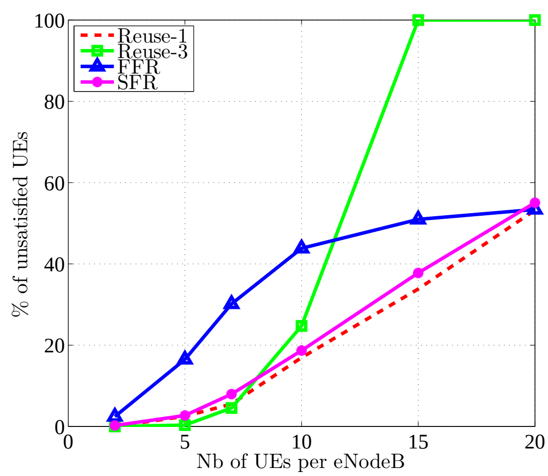

Fig. 9: UE satisfaction versus network load

We notice that reuse-3 model shows the lowest percentage of unsatisfied UEs for low network loads. When each cell is using a disjoint part of spectrum, ICI problems are largely eliminated. However, the percentage of unsatisfied UEs becomes the highest among all the compared techniques when the network load increases. Only one third of the available spectrum is used in each cell; thus, network capacity and UE satisfaction are reduced when network load increases.

Despite of the power reduction over RBs allocated for GR UEs, SFR shows approximately the same percentage of unsatisfied UEs as for reuse-1 model. The power allocation strategy reduces ICI, especially for BR UEs, and GR throughput loss is compensated. Compared to reuse-1 model, FFR increases the percentage of unsatisfied UEs, due to restrictions on RB usage between network cells. A portion of the available spectrum is not allowed to be used in each cell. When network load increases, FFR performance becomes better than that of reuse-3 model. It is a compromise between reuse-1 model and reuse-3 model. In fact, when using FFR, we guarantee that BR UEs of adjacent cells operate on disjoint spectrum. Thus, it makes use of the main advantage of reuse-3 model: ICI is mitigated for BR UEs. Moreover, it avoids the disadvantage of reuse-3 model $i.e.$, the lack of RBs available in each cell, by allowing the usage of reuse-1 model in GR zones of the neighboring cells.

E. UE Satisfaction versus UE Distribution

The particularity of our work is that we compare the performance of different ICIC techniques under both homogeneous and non-homogeneous UE distributions. When UEs are homogeneously distributed between cell zones, the percentage of GR UEs is close to or equals 50%. In other words, half of the active UEs are GR UEs, while the other half are BR UEs. However, when non-homogeneous UE distributions are considered, the majority of active UEs are either in GR zone (when the percentage of GR UEs is greater than the percentage of BR UEs), or in BR zone (when the percentage of BR UEs is greater than the percentage of GR UEs). In this paragraph, we consider seven adjacent cells with 10 UEs in each cell. UE positions are generated in a manner that the percentage of GR UEs varies between 20% and 80%. For each UE distribution (percentage of GR UEs), simulations are repeated 100 times, and the obtained results are reported in Fig. 10.

According to these results, FFR reduces the percentage of unsatisfied UEs in the network when their distribution is approximately homogeneous between BR and GR zones. It improves system performance in comparison with reuse-1 model when 50% to 70% of active UEs are GR UEs. However, when the majority of active UEs are either in the BR zone, or in the GR zone, the percentage of unsatisfied UEs exceeds that of reuse-1 model. FFR is a static technique, and RB

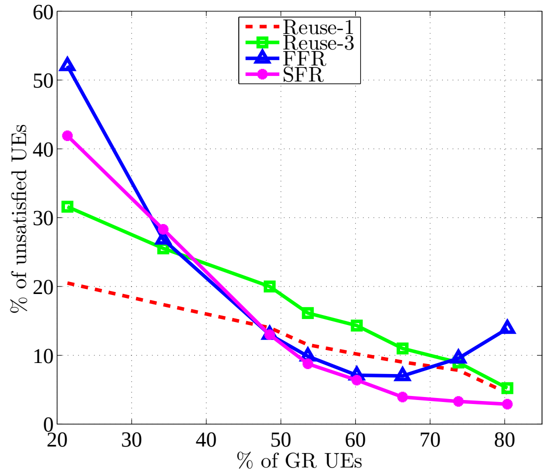

Fig. 10: UE satisfaction versus percentage of GR UEs

distribution among GR and BR zones is not dynamically adjusted according to UE distribution. The same static aspect appears with SFR, where UE satisfaction is not better than reuse-1 when the majority of UEs are BR UEs. However, SFR reduces the percentage of unsatisfied UEs when more than 50% of active UEs are GR UEs. Reuse-3 technique increases the percentage of unsatisfied UEs when compared to reuse-1 model, for all UE distributions. Restrictions made on RB usage in each cell reduces spectrum profitability, which in turn has a negative impact on the achievable throughput.

We also conclude that static configuration parameters for FFR and SFR can be adjusted to meet UE distribution between BR and GR zones. The choice of these tuning parameters [30, 35] is made by mobile network operators according to quality of service requirements and deployment scenarios.

F. Fairness Index versus UE Distribution

For the same simulation scenario, we study UEs throughput fairness index when the percentage of GR UEs in the network changes. For each UE distribution, simulations are repeated 100 times, and the obtained results are shown in Fig. 11.

Reuse-3 model shows permanently the highest throughput fairness index among all the studied techniques. It exceeds Jain's fairness index of reuse-1 model, where BR UEs suffer from ICI, which has a negative impact on their throughput, while GR UEs achieve higher throughputs. The

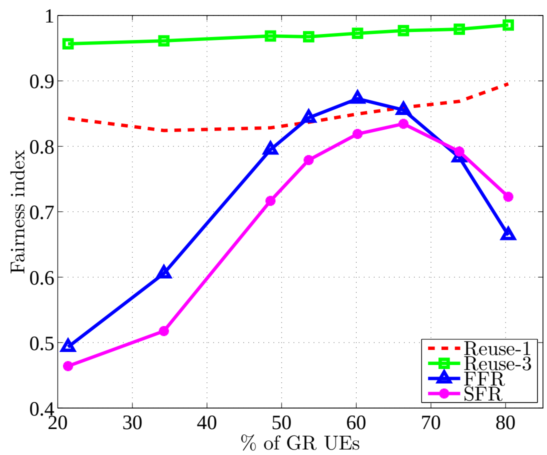

Fig. 11: Fairness index versus percentage of GR UEs

static RB and power distributions between BR and GR zones, applied in FFR and SFR, are not adequate for all UE distributions, especially when the majority of active UEs are homogeneously distributed between cell zones. Although they succeed in reducing ICI, FFR and SFR do not improve throughput fairness among all UEs for these particular scenarios. Nevertheless, FFR improves Jain's fairness index in comparison with reuse-1 model when 55% to 65% of UEs are GR UEs. Thus, FFR tuning parameters should be adjusted according to network load and UE distribution between the different zones.

G. Spectral Efficiency and Energy Efficiency versus UE Distribution

We also study the impact of UE distribution on spectral and energy efficiencies, for reuse-1, reuse-3, FFR and SFR techniques. Simulation results concerning spectral and energy efficiencies are reported in Fig. 12 and Fig. 13, respectively.

According to the obtained results, SFR shows the highest spectral efficiency, since it allows using all the available spectrum in every cell, while imposing restrictions on power allocation for RBs available in each zone. Therefore, it succeeds in reducing ICI while increasing spectral efficiency for all UE distributions, except the case where the majority of UEs are GR UEs: in this case, reuse-1 model is better since it achieves higher throughputs without the need to reduce downlink transmission power. SFR has also the highest energy efficiency in comparison with reuse-1, reuse-3 and FFR techniques.

Energy efficiency for reuse-3 model exceeds that of reuse-1 and FFR techniques, since no

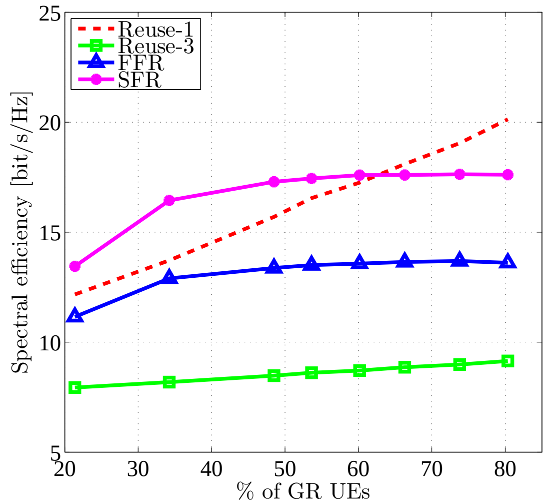

Fig. 12: Spectral efficiency versus percentage of GR UEs

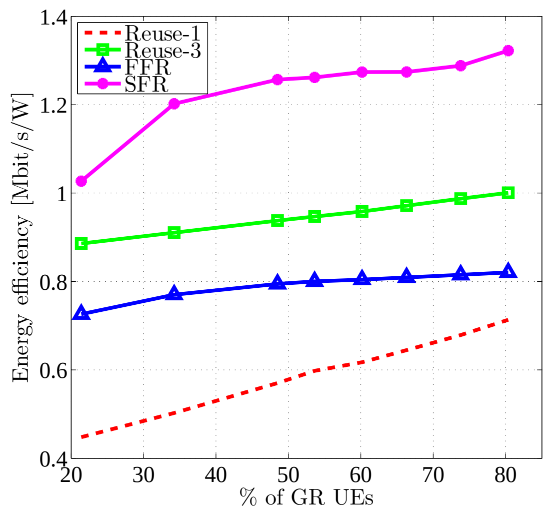

Fig. 13: Energy efficiency versus percentage of GR UEs

downlink power consumption is made on unused RBs (two thirds of the available spectrum in each cell are unused). Restrictions on RB usage make reuse-3 technique the one with the lowest spectral efficiency: in a cluster of three adjacent cells, only one third of the available spectrum is used in each cell. FFR is a compromise between reuse-1 and reuse-3 in terms of spectral and energy efficiencies. Indeed, reuse-1 model is used in GR zones, while reuse-3 model is used for BR zones of the adjacent cells.

VI. CONCLUSION

The increasing demands for data in mobile networks, as well as the exponential growth in mobile applications have obliged mobile network operators to choose dense frequency reuse model to improve spectral efficiency and increase network capacity. However, inter-cell interference problems has a negative impact on UE throughput and system performance. ICIC techniques are proposed to mitigate ICI, and to improve UEs throughput without largely reducing spectral efficiency.

In this article, we surveyed traditional ICIC techniques, such as reuse-3 model, FFR, and SFR techniques, and we compared them to reuse-1 model. System-level simulations are made under uniform and non-uniform UE distributions. They allow us to study the performance of each technique, for several parameters: spectral efficiency, energy efficiency, mean throughput per zone, throughput fairness index, and UE satisfaction. Reuse-3 shows the lowest spectral efficiency, while SFR improves it in comparison with reuse-1 model. FFR technique is a compromise between reuse-1 and reuse-3 model. However, FFR and SFR are static ICIC techniques, and they require interventions from mobile network operator to adjust RB and power distribution between cell zones according to UE distribution and quality of service demands.

In order to overcome the limitations of the existing ICIC techniques, we proposed in a subsequent work [44] a non-cooperative ICIC scheme that improves SFR performance without the need to exchange additional signaling messages between the different cells. We also introduced a distributed cooperative ICIC scheme [62] that adjusts resource and power allocation between the different cells in a collaborative manner. This technique makes use of the signaling messages exchanged between the adjacent cells over X2 interface.

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